CONTROL AND NON-PAYLOAD COMMUNICATIONS LINKS FOR INTEGRATED UNMANNED AIRCRAFT OPERATIONS

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Abstract

Technology for unmanned aircraft has advanced so rapidly in recent years that many new applications for public and commercial use are being proposed and implemented. In many countries, emphasis is now being placed on developing the means to allow unmanned aircraft to operate within non-segregated airspace along with commercial, cargo and other piloted and passenger-carrying aircraft. In the United States, the Congress has mandated that the Federal Aviation Administration reduce and remove restrictions on unmanned aircraft operations in a relatively short time frame. To accomplish this, a number of technical and regulatory hurdles must be overcome. A key hurdle involves the communications link connecting the remote pilot located at a ground control station with the aircraft in the airspace, referred to as the Control and Non-Payload Communications (CNPC) link. This link represents a safety critical communications link, and thus requires dedicated and protected aviation spectrum as well as national and international standards defining the operational requirements of the CNPC system. The CNPC link must provide line-of-sight (LOS) communications, primarily through a ground-based communications system, and beyond-line-of-sight (BLOS) communications achieved using satellite communications. In the United States, the National Aeronautics and Space Administration (NASA) is charged with providing the technical body of evidence to support spectrum allocation requirements and national and international standards development for the CNPC link. This paper provides a description of the CNPC system, an overview of NASA's CNPC project; and current results in technology assessment, air-ground propagation characterization, and supporting system studies and analyses will be presented.

Introduction

Unmanned aircraft, also referred to as remotely piloted aircraft, have emerged as the most significant vehicular advancement affecting airspace operations today. As a result of the requirements of military operations during the past decade, unmanned aircraft have rapidly reached a level of technological advancement whereby many non-military uses are now proposed. These non-military uses will often require operations in the same airspace as commercial and general aviation aircraft.

The integration of unmanned aircraft operations into the general airspace is now being researched with some urgency, as there is considerable pressure from the industry and public organizations to enable such operations for enhanced public safety, scientific research, agriculture, cargo, and many other public, commercial for-profit and not-for-profit applications. In particular, in the United States the Congress has mandated that the Federal Aviation Administration (FAA) quickly develop policies and procedures to reduce the constraints on the integration of UAS operations within the National Airspace (NAS). The key issue preventing such integration is a lack of developed standards for unmanned aircraft system (UAS) operations, as all previously developed standards and policies were based upon manned operations. The requirements for a UAS to be certified to enter the airspace and be able to respond to air traffic control and avoid other aircraft and terrain are now being defined. Aircraft and

system certification, sense and avoid techniques, air traffic management procedures, aircraft control human interfaces, and communications links are among the major elements of UAS integration now being studied. In the United States, the RTCA Special Committee 203 (SC-203), consisting of industry and government members, is coordinating the development of standards for UAS that will enable FAA certification of UAS for NAS operations.

To address the US urgency to enable the integration of UAS into the NAS, NASA has been called upon to help provide several key technical developments to support the acceleration of UAS integration, in particular for areas not under the auspices of other organizations and not being undertaken by industry. To accomplish this, NASA has established the 5-year Unmanned Aircraft Systems (UAS) Integration in the National Airspace System (NAS), or UAS in the NAS Project [1]. The Project's objectives are:

- Develop a body of evidence (including validated data, algorithms, analysis, and recommendations) to support key decision makers in establishing policy, procedures, standards and regulations, enabling routine UAS access in the NAS.
- Provide methodologies for development of airworthiness requirements and data to support development of certification standards and regulatory guidance.
- Support development of a national roadmap.
- Establish the infrastructure for the integrated test and evaluation (IT&E) environment for simulations and flight demonstrations.

To accomplish these objectives, the following five UAS in the NAS sub-projects are being executed.

- Separation Assurance/Sense and Avoid Interoperability (SSI), with the objectives of assessing the applicability to UAS and the performance of NASA NextGen separation assurance concepts in flight tests with realistic latencies and trajectory uncertainty, and providing an assessment of how NextGen separation assurance systems with different functional allocations perform for UAS in mixed operations with manned aircraft.

- Human Systems Integration, with the objectives of developing a research test-bed and database to provide data and proof of concept for GCS operations in the NAS and coordinating with standards organizations to develop human factors guidelines for GCS operation in the NAS.

- Communication, with the objectives of developing data and rationale to obtain appropriate frequency spectrum allocations for the safe and efficient operation of UAS in the NAS; developing and validating candidate UAS CNPC system/subsystem test equipment which complies with UAS international/national standards and frequency regulations for UAS; perform analysis and propose CNPC security recommendations for UAS operations; and performing analysis to support recommendations for integration of CNPC and ATC communications to ensure safe and efficient operation of UAS in the NAS.

- Certification, with the objectives of developing methodology for Classification of UAS and Determination of Airworthiness standards for avionics aspects of UAS and developing hazard and risk related data to support development of regulation.

- Integrated Test and Evaluation (IT&E) will for orchestrate the major integrated simulation and flight test series events. IT&E integrates the individual technology development simulation and flight test series objectives into executable tests and provisions for an appropriately complex relevant test environment to aide in developing each Subproject's concepts, technologies, and capabilities and in evaluating the overall operation of UAS in the NAS.

The Communication Sub-Project, being performed by NASA's Glenn Research Center, is responsible for the developing the technical body of work for CNPC system standards and spectrum, and is the primary subject of the remainder of this paper. In the next sections of the paper, the requirements and proposed communications architectures for CNPC will be described, followed by the status of spectrum for LOS and BLOS CNPC. NASA's Communication Sub-Project will then be described, and current sub-project plans and results for CNPC system technology assessment, air-ground propagation characterization, and supporting system studies and analyses will be presented.

CNPC Requirements and Architectures

The possible communications interfaces for unmanned aircraft system operations in the NAS are shown in Figure 1, based on analyses provided through RTCA SC-203. The UAS as a system includes the unmanned aircraft (UA), the control element (CE) which includes the remote pilot and the ground control station (GCS), and the surveillance element (SE) which enables both internal and external entities to obtain situational awareness of the UAS location and surrounding air traffic. Interacting with the UAS are various navigational aids, surveillance systems, separation assurance and see-and-avoid systems, mission control and flight planning, and air traffic control. The CNPC link includes the communications elements between the UA and CE, specifically telecommands to the aircraft and telemetry from the aircraft. It may also include information downlinked from the aircraft to the GCS coming from navigational, surveillance, separations assurance/see-and-avoid systems, in both data and video form. Air traffic control communications, either voice or data, both to and from the remote pilot, may also be relayed through the CNPC link.

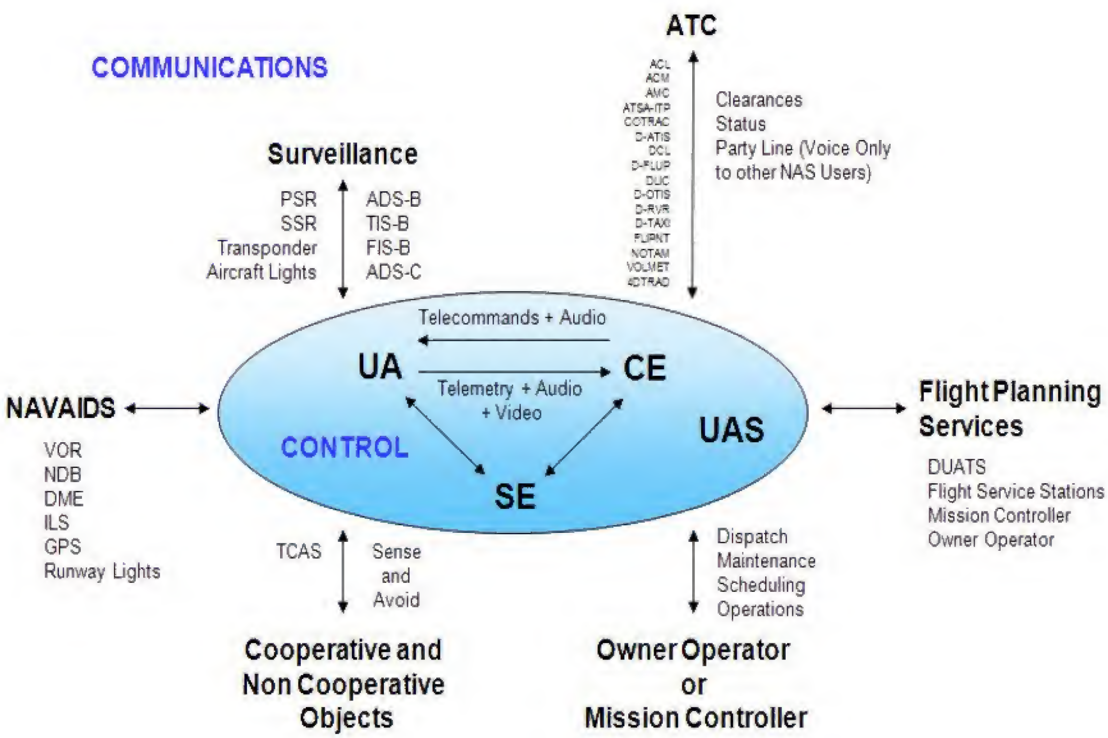


Figure 1 - Communications Interfaces for UAS Operations [RTCA SC-203]

Estimates of the CNPC data communications requirements have been developed through RTCA SC-203 and other sources, and have been reported in [2]. They are summarized as follows, where a small UA is less than or equal to 55 kg in mass, while medium/large UAs are greater than 55 kg in mass.

- Uplink Information Rates (Ground-to-Air):
  - Small UA: 2,424 bps
  - Medium and Large UA: 6,925 bps
- Downlink Information Rates (Air-to-Ground)
  - Small UA (basic services only): 4,008 bps
  - Medium and Large UA (basic services only): 13,573 bps
  - Medium and Large UA (basic and weather radar): 34,133 bps
  - Medium and Large UA (basic, weather radar and video): 234,134 bps

The CNPC link is expected to support this range of data rates. In addition, the expected total number of UAS that must be supported by the CNPC system projected to the year 2030 is also specified in [2] in terms of density of UAS in space: Small UAs = 0.000802212 UA/ km^2; Medium UAs = 0.000194327 UA/ km^2; and Large UAs = 0.00004375 UA/ km^2. This description allows the

number of UA in a given communications service volume that the CNPC link would need to service to be computed. For example, a terrestrial-based CNPC link with 100 km radius could contain up to 1680 small UAS, 407 medium UAS, and 91 large UAS. An important requirement of the CNPC system is the ability to provide 20 individual control messages per second for UAS that require real-time control (e.g. joystick control), in other words a frame rate of 20 Hz will be required for some UAS.

RTCA SC-203 has defined possible communications architectures to service the requirements of UAS integration. These architectures include air traffic control elements (communications between air traffic control and the remote pilot) and control and non-payload communications (CNPC), providing the communications between the remote pilot ground control station and the aircraft. For CNPC, there will be both line-of-sight (LOS) communications systems (direct communications between the aircraft and the ground) and beyond-line-of-sight (BLOS) communications (non-direct communications between the aircraft and ground, such as through a satellite communications link, or through a distributed network of LOS ground stations). A general CNPC system architecture which takes these requirements into account is shown in Figure 2.

LOS CNPC links are direct LOS connections between the GCS and the UA. BLOS CNPC links could be implemented using a network of CNPC ground stations when such a network is available, or through satellite communication links where such a network is not available (remote or oceanic locations, or other locations where UAS ground station network infrastructure is not available). Air Traffic Control (ATC) and Air Traffic Services (ATS) communications are performed using the same VHF voice and data communications links used for manned aircraft. These voice and data messages are relayed through the UAS CNPC link to and from the pilot located at the GCS. In the future, some or all ATC and ATS communications will be performed over ground-based systems when the infrastructure becomes available.

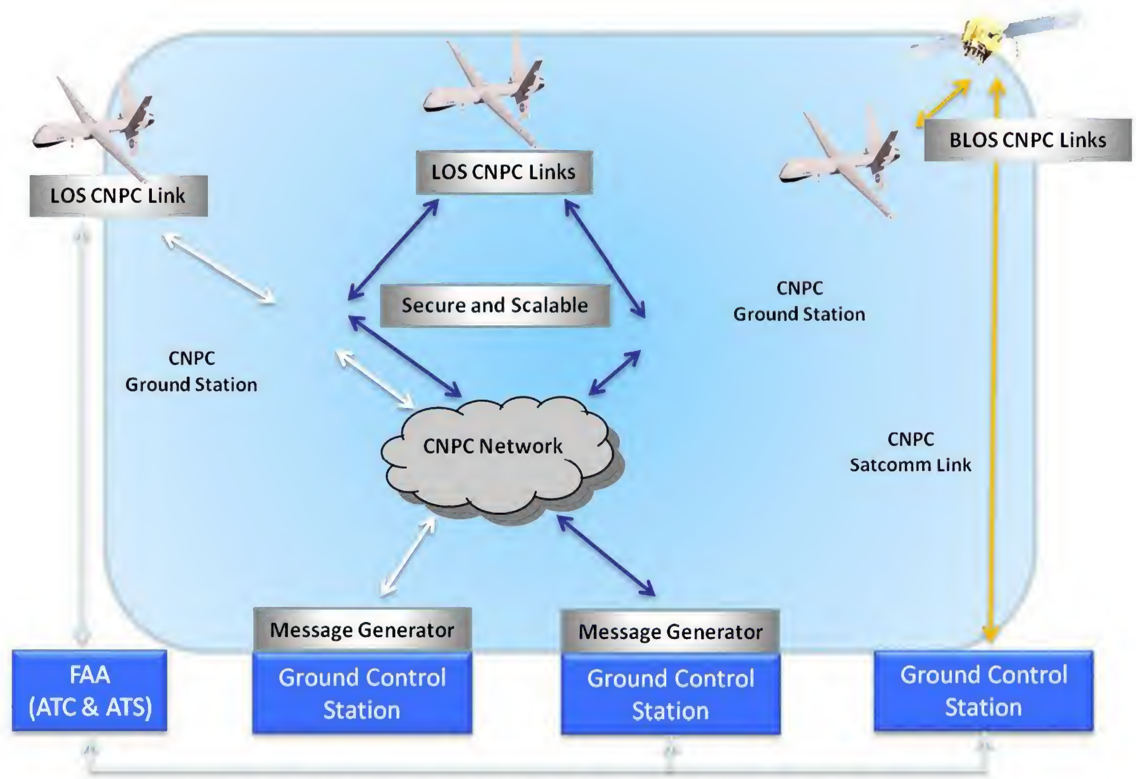
Spectrum for LOS and BLOS CNPC

The CNPC link provides safety critical information for the control of UAS. To enable the integration of UAS into non-segregated airspace, the CNPC link is required to use protected aviation spectrum. The standards and spectrum requirements for CNPC systems for UAS must be based on reasonable estimates of the future data communications requirements. Considering the data rate requirements and expected UA density as described in the previous section, the UAS CNPC bandwidth requirements for the year 2030 are 34 MHz for the terrestrial-based LOS CNPC and 56 MHz for the satellite based BLOS CNPC links [2].

Prior to the 2012 International Telecommunications Union (ITU) World Radiocommunications Conference (WRC-12), no allocation of spectrum for UAS CNPC existed. At WRC-12, a new allocation for terrestrial aviation safety spectrum designated as Aeronautical Mobile (Route) Service, or AM(R)S was approved in the band 5030-5091 MHz. However, this band is also allocated to Aeronautical Mobile Satellite (Route) Service or AMS(R)S. Hence the 61 MHz in this band is inadequate to meet the combined 90 MHz spectrum requirement for LOS and BLOS CNPC. An AM(R)S allocation in the 960-1164 MHz band was also approved. It is intended to potentially meet future ATC requirements but may also provide for some CNPC requirements. In particular, the 960-977 MHz portion of the band is considered to be suitable for CNPC systems. The remaining 977-1164 MHz includes a number of incumbent surveillance and navigation systems such that it would be very difficult to share this spectrum between those systems and CNPC.

With the CNPC allocation approved at WRC-12, it is possible now to consider the development of standards for CNPC terrestrial LOS systems. NASA’s activities towards that end are discussed below. However, the BLOS satellite-based CNPC system still faces obstacles.

The 5030-5091 MHz AMS(R)S allocation is intended for UAS CNPC. However there are no current satellites operating in that band, nor are any planned in the foreseeable future. It is likely that there is not a large enough market for UAS BLOS CNPC systems to provide a satellite service provider sufficient revenue to justify the investment necessary to develop and launch such a system, at least without considerable government funding. Therefore, the use of existing satellites operating in the fixed satellite service (FSS) is being proposed for BLOS CNPC, which would allow the development of and validation of CNPC standards, enabling rapid implementation of BLOS CNPC.



Possible Future ATC and ATS Ground Connectivity

The use of FSS for UAS CNPC faces many hurdles involving both technical issues and policy. The FSS bands are not protected aviation spectrum, so using these bands means a very high burden of proof that CNPC systems would be compatible with other systems in the FSS bands while still providing the availability required for a safety critical communications link. The next WRC scheduled for 2015 includes an agenda item to consider the use of FSS bands for CNPC. Compatibility studies are being undertaken by NASA and other organizations, and approaches to policy issues such as coordination of services, and definition of safety margins and availability requirements are now being investigated in preparation for WRC-15.

UAS in the NAS Communications Sub-Project

The UAS in the NAS Communication Sub-Project at NASA's Glenn Research Center is focused on the development of technical information necessary to enable the approval of the CNPC spectrum allocations and the development of national and international standards for CNPC systems [3]. The standards and spectrum allocations will enable the development of CNPC systems that can be certified for use by UAS operations in non-segregated airspace. As discussed in the previous sections, spectrum allocations now exist for terrestrial LOS CNPC systems, while spectrum allocations for BLOS CNPC satellite-based communications are inadequate. Hence the Sub-Project is focused on CNPC standards development for the LOS terrestrial element and the development of technical material to support further satellite communications spectrum allocations for BLOS CNPC systems.

For the satellite communications spectrum allocation activity, the Sub-Project is developing analyses to support compatibility studies for CNPC systems operating in FSS bands, in particular the 14.0-14.5 GHz and 27.5-30.0 GHz bands, although other FSS bands may also be analyzed. Analyses in support of other policy issues as described in the previous section will also be developed.

Technical information for the development and validation of terrestrial LOS CNPC standards will come from the characterization of the air-ground propagation channel, the development and testing of CNPC

airborne and ground test radios, the development and validation of security vulnerability mitigation methods, and modeling and simulation of CNPC systems from individual link to NAS-wide simulations.

NASA has entered into a cooperative agreement with Rockwell-Collins Inc. to developed three iterations of CNPC radio prototypes. These test radios will be evaluated in flight testing during the course of the 5-year project. The test radio design is being developed from technology assessments and trade studies, channel propagation models, requirements analyses and system-wide modeling and simulation, as well as initial draft standards. They will be built to operate in both of the potential CNPC terrestrial AMS(R)S bands – L-band (960-977 MHz) and C-band (5030-5091 MHz). The results of radio testing and analysis will be used to assess the CNPC requirements and standards and enable them to be modified to meet real-world physical constraints and practical implementation issues. The end result is intended to be complete CNPC system standards to which manufacturers can build certifiable radios for all UAS applications.

A technology assessment activity to identify the best existing communications technology for the CNPC requirement has been completed by NASA. This study, described in the next section, is forming the basis of the initial CNPS test radio in combination with waveform trade studies undertaken by Rockwell-Collins, Inc.

The following section will describe the flight testing campaign that will be undertaken in the last four months of 2012 to characterize the air-ground propagation channel for the terrestrial CNPC system. The test results will be used to develop a channel model against which CNPC communications systems can be analyzed to optimize the design of the CNPC test radios.

The final section will describe plans for system analysis based on modeling and simulation of the CNPC links and their application to, and interaction with the NAS. The resulting analyses will be used to assess how well the CNPC system standard meets the UAS performance requirements.

LOS CNPC System Technology Assessment

NASA has completed a study to assess communications technologies for application to the terrestrial LOS CNPC requirements. In this study [4], existing technologies that can be tailored for use as the UAS CNPC link and implemented in the NASA CNPC test radio were identified and were prescreened against basic requirements. The technologies that survived the prescreening were then more rigorously evaluated against a set of criteria reflecting the detailed requirements for the CNPC link, resulting in a remaining small set of the most applicable candidate technologies.

The technologies that were identified for study included more than 50 distinct currently existing technologies grouped into the following categories: Cellular Telephony Derivatives; IEEE 802 Wireless Derivatives; Public Safety and Specialized Mobile Radio; Custom civil/Aeronautical Solutions; Military; and APC Telephony.

The technologies that were considered needed to be suitable for the CNPC link in terms of availability, integrity, and continuity of function; data traffic requirements; complexity/certification risk; and waveform compatibility. The technology must also be capable of being on the path for standardization and certification. To reduce the number of technologies that needed rigorous evaluation, the technologies were prescreened against the following minimum threshold criteria: non-proprietary with open standards and exportable; sufficiently mature; able to support a regular and reliable channel access rate for control of the UA; and sufficiently dissimilar to other evaluated technologies.

24 technologies survived the prescreening process and were further evaluated against 31 evaluation criteria grouped into these categories:

- Air/Ground Communications - Does the technology support necessary ranges for UAS flight?
- Data transmission - Can the technology support the data requirements of the identified traffic?
- Mobility - Does the technology have features to support mobility?
- Security - Does the technology support message confidentiality and integrity?
- Traffic QoS - Does the technology support a variety of QoS levels for the different UA traffic?
- Certification / complexity - How difficult will the technology be to build and certify for UAS?
- Waveform - How well does the technology match the proposed waveform?

The results of the technology assessment showed that no technology is a perfect match for the CNPC system. All technologies must be modified to match the proposed waveform and all technologies need to be tested at intended distances and speeds. The study identified the 4 best technologies to be the IEEE 802.16 wireless broadband standard and the Long Term Evolution (LTE) wireless high speed data communication standard, followed by Public Safety Communications Standard APCO Project 34/ Telecommunications Industry Association Standard 902 (P-34/TIA 902) and TETRA Enhanced Data Service (TEDS). These identified technologies performed very well in the data transmission, mobility, and QoS categories and do not have any identified issues with modification to support the proposed waveform.

The four identified final candidates received further review and development as potential CNPC systems. In this process, a high-level overview of "how it works" was developed to identify any issues or areas that need further exploration. For each technology, potential approaches were described and a review of the features of each technology was conducted to identify which features are desirable, and which are unnecessary. The framing approach was examined to understand how it would be modified for the Rockwell-Collins recommended physical layer. Other critical issues that were examined included network entry and initialization, data transfer method and handoff procedures. As result of these final analyses, 802.16 was selected as NASA's preferred technology for the terrestrial LOS CNPC system. Further details are provided in [4].

LOS Air-Ground Channel Characterization

Accurate wideband channel models are very useful for analyzing the performance of the CNPC systems planned for implementation in the two bands available for these systems – L-band and C-band. However, extensive literature surveys have revealed that no accurate, validated wideband models exist for the air-ground channel in either L or C-bands allocated for UAS. Airframe shadowing models also do not yet exist. Therefore NASA will perform flight and ground measurements in order to obtain the data necessary to develop air-ground channel models for UAS, in both the L & C Bands.

For the air-ground channel measurements, a custom, dual-band single-input/multiple-output (SIMO) channel sounder is being procured by NASA from Berkeley Varitronics Systems (BVS). The channel sounder will measure power delay profiles (PDPs), taken simultaneously from two spatially separated receive antennas in each of the L- and C-bands (i.e., two Rx antennas for each band). PDPs will be taken at a high sample rate (up to 3 kHz) in order to enable measurement of Doppler characteristics PDPs are obtained using the procedure of a stepped correlator receiver that operates on the received direct-sequence spread spectrum signal sent from the companion transmitter. The approximate signal bandwidths in the two bands are 5 MHz in the L band, and 50 MHz in the C band, corresponding to delay resolutions approximately 200 ns in L band, & 20 ns in C band and distance resolutions between multipath components (MPCs) of 60 m and 6 m, respectively. From sequences of measured PDPs (& MPC phases), the multipath channel impulse response and its time variation will be quantitatively characterized for each environment. Analysis of the PDPs will yield information on fading amplitude statistics, delay spreads, frequency-domain characteristics (e.g., coherence bandwidths), and Doppler spreads for each SIMO channel in each band. Channel parameter correlations across the two bands and across receive antennas will be evaluated.

From all of these results, statistical channel models will be developed for each environment or setting. These models must be developed for a number of different types of terrain and also need to consider other parameters such as antenna height, location, and elevation angle. The resulting models will be of tapped-delay line form.

The measurements will be made for a number of different terrain and geographic settings including: Open, over water; Flat land with urban, suburban, rural, desert and forest terrain; Hilly land with urban, suburban, rural, desert and forest terrain; and Mountainous - adjacent to one range and among multiple mountains. Various ground station settings will be tested, such as open area, open with some clutter nearby, and obstructed/heavy clutter. Variations of antenna height and gain/beamwidth will also be tested. Various flight path trajectories will be needed, such as toward and away from the ground stations, large-radius arcs, banking turns, takeoff and landing. The test equipment and flight schedules are being prepared to enable completion of these tests during the last four months of 2012.

CNPC System Analysis

NASA will perform extensive CNPC system analyses based upon modeling and simulation of the CNPC system and integration of these models into single link, regional and NAS-wide simulations.

Modeling and simulation of the CNPC link will provide validation of CNPC system models for use in larger scale simulations. Models will be validated against test data from flight testing of the CNPC test radios, allowing the models to be refined and improved. The OPNET™ commercial network performance software tool will be applied to the CNPC system model development.

Regional and NAS-wide simulations will employ the CNPC models integrated into NASA's Airspace Concept Evaluation System (ACES). ACES is a non-real-time modeling and simulation system with full gate-to-gate representation of all the major components of the NAS, in which the individual behaviors of the airspace participants are modeled [5]. ACES Build 4 is now operational and has been utilized to address multiple advanced ATM concept analyses as well as futuristic NAS demands including 2 and 3 times increased traffic levels. Additional development of ACES is underway to enable UAS aircraft to be included in simulations. Communications enhancements have also been made to ACES in preparation for CNPC simulations.

Conclusions

In order to enable UAS operations in non-segregated airspace, a robust, secure CNPC system standard must be developed for use in protected aviation spectrum or equivalent spectrum. The CNPC system includes a terrestrial-based LOS and terrestrial-networked and satellite communication-based BLOS element. New spectrum allocations recently approved at WRC-12 provide spectrum for the development of the terrestrial LOS CNPC element, but further work is needed to enable satellite-based CNPC systems to be developed as the currently available band for satellite-based CNPC is not serviced by any existing satellites.

NASA's UAS in the NAS Communication Subproject is developing the technical body of work necessary to support the completion of national and international standards for the LOS CNPC system, and for a useable CNPC satellite spectrum allocation. NASA is teaming with Rockwell-Collins Inc. to develop several CNPC test radios, based on existing CNPC requirements and the results of recent technology and waveform assessments. A flight campaign will be undertaken shortly to characterize and model the air-ground propagation channel in the two available bands for LOS CNPC – 960-977 MHz and 5030-5091 MHz. The security of the CNPC link is being investigated and techniques for mitigation of potential vulnerabilities are being developed. An extensive modeling and simulation effort will enable full NAS-wide simulations of candidate CNPC systems to evaluate performance and impact on the NAS. These activities will enable completion of national and international standards for LOS CNPC such that manufacturers will be able to provide certifiable CNPC systems to UAS operators to enable integration of UAS into the NAS.

References

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